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Development of building integrated photovoltaic (BIPV) system with PV ceramic tile and its application for building façade

Yen-Chieh Huang[1], Chi-Chang Chan[2], Shui-Jinn Wang[1, 3], Shin-Ku Lee*[4]

[1]Institute of Microelectronics, Department of Electrical Engineering, National Cheng Kung University, Tainan 701, Taiwan
[2] Green Energy & Environment Research Laboratories, Industrial Technology Research Institute
[3] Advanced Optoelectronic Technology Center, National Cheng Kung University, Tainan 701, Taiwan
[4]Research Center for Energy Technology and Strategy, National Cheng Kung University

Abstract

In this paper, the single-crystal silicon-based solar cells laminated between tempered glass and ceramic tile is developed to be utilized in the building's façade. Firstly, the electrical, optical, and thermal properties of the proposed PV module are evaluated. Then, the wind-resistance test is implanted to evaluate the installation feasibility in Taiwan where have typhoon frequently. The electrical and deflection characteristics of the proposed PV module have no obviously changed after a 50 thermal cycling test and a 200 hour humidity-freeze test, based on IEC 61215, and a wind-resistance test, respectively. Finally, electrical power generation of the proposed BIPV system with 1 kWp electrical power capacity installed in a demonstration house is performed. The experimental results indicate that accumulative power generation is 185 kWh during 6-month monitoring period. And that, the exterior temperature of the demonstration house is lower than that on the surface of the BIPV system about 10°C. The proposed BIPV system not only provides the passive energy for its power loading, but also improves the indoor thermal environment by fluent natural ventilation.

BIPV, ceramic tile, dry-suspended method, net zero-energy building

1. Introduction

The Green House Gases (GHG) emission such as carbon dioxide, nitrogen sulfide, and fluorine carbonate, has influenced the global environment and results in the rising of annual earth temperature [1]. Solar energy is one of the renewable energy resources that can be easily obtained. Moreover, solar energy is inexhaustible and has no pollutant problems. On the state-of-the-art of photovoltaic (PV) systems development, building incorporated photovoltaic (BIPV) has become the most promising and potent technology. Compared with traditional non-integrated PV systems, BIPV not only requires no extra allocation place, brackets, and rails for installation, but also offers instantaneously electrical power for buildings such as indoor air-conditioning and illumination. BIPV can replace the traditional envelopes on building like roof, window, façade and shading systems, and attract architectural interest to it. In addition, the shaded face of a BIPV system can also be used as shade from the sun, reducing the heat absorption by the building and thus, decreasing the energy consumption and interior temperature [2].

In this study, a BIPV system composed of PV ceramic tile module is installed in a demonstration house. The PV module composed of single-crystal silicon solar cells is shown in Fig. 1. The length, width, and thickness of the proposed PV tile module are 40, 40, and 12 mm, respectively, and the PV cells are laminated between tempered glass and ceramic tile substrate by ethylene vinyl acetate (EVA) copolymer. And the solar cells are each serially connected to throughput electrical power. Final the electrical, optical, and thermal properties of the proposed PV module are evaluated. The BIPV system is directly hang on the vertical wall of the demonstration house by a novel dry-suspended method, and the wind-resistance test based on the ASTM E330 [3] standard is implemented to evaluate the structural performance of the PV module. The experimental house faces to the southeast on the vertical siding and it is built at the Industrial Technology Research Institute (ITRI), where the location is 24°46' North Latitude and 121°02' East Longitude in north Taiwan, and the electrical power generation performance of the proposed BIPV

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* Corresponding author. Tel.:+886-6-2757575 ext. 31450; fax:+886-6-2369715.
E-mail address:sklee1015@gmail.com.

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system is investigated for the practical installation during six-month monitor in Taiwan. This paper presents an intensely interesting data for the development of BIPV system compacted with PV ceramic tile.

2. Performance tests

2.1 Electrical, optical, and thermal properties of PV tile module

The maximum power determination tests are performed under standard test conditions, which corresponded to 1000 W/m^2 at a cell temperature of 25±2^{o}C, with an air mass AM$_{1.5}$ solar spectral irradiance. The electrical characteristics regarding to the proposed PV module's open circuit voltage (V_{oc}), short circuit current (I_{sc}), fill factor (FF) and maximum power determination are measured shown in table 1. Further, there is no significant difference revealed in terms of the electrical characteristics of the PV module after a 50 thermal cycling test and a 200 h humidity-freeze test based on the IEC 61215 standard [4].

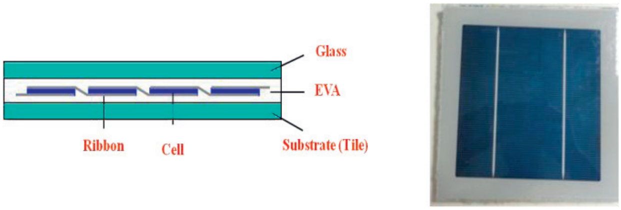

Fig. 1 Schematic diagram of proposed BIPV module

Table 1 Results of maximum power determination test

Class: A	STC	E: 1000 W/m²	Temp: 25℃
Items	Unit	Before test	After test
V_{oc}	[V]	0.608	0.610
I_{sc}	[A]	7.725	7.709
P_{max}	[W]	3.418	3.430
FF	[%]	72.690	72.930

Table 2 shows the optical properties of the proposed BIPV module. UV-Vis transmittance and reflectance spectra are recorded using a Lambda 900 UV-VIS-NIR spectrophotometer (Perkin-Elmer, UK). Spectral transmittance/reflectance measurements of samples are carried out to determine optical properties in the spectral range of solar radiation. It means the wavelength interval between 300 nm and 2500 nm based on ISO 9050 [5]. In addition, the emissivity of samples is determined on a FTIR spectrophotometer (Perkin-Elmer, UK). FTIR spectra are recorded in the range from 400 cm^{-1} to 4000 cm^{-1} with a resolution of 4 cm^{-1} and averaged over 25 scans.

Table 2 Optical properties of the proposed PV module

Item	PV module	Item	PV module
UV transmittance	0	Solar irradiation transmittance	0
UV reflectance	5.40	Solar irradiation reflectance	8.45
Visible light transmittance	0	Emissivity front side (Outdoor)	0.837
Visible light reflectance	5.45	Emissivity Back side	0.927

In our early work, the small-sized hot-box test with a solar simulator lamp is designed [6] to evaluate the thermal performance of PV module. The walls of the chamber are composed of 0.05 m thick Styrofoam plates. The inner surfaces of the chamber are painted black to prevent the light from being reflected and diffused away from the sample surface. A Xenon Arc lamp of 1000 W is chosen as a solar simulator lamp to provide the incident radiant energy. The Xenon Arc lamp with reference to sample is positioned to achieve a homogenous distribution of radiant intensity across the whole sample surface area. Six K-type thermocouples are used to measure the surface temperature on both sides of the sample, and two K-type thermocouples are used to measure the exterior and interior ambient temperatures, respectively. Figure 2 presents the surface temperature of the exterior and interior sides of the proposed PV module. The steady temperature of exterior surface of PV module was 72^{o}C, and the other side was 65^{o}C. The temperature on the exterior surface is greater than that on the other side, due to the high heat-absorptive ability of the ceramic tile.

2.2 Wind-resistance test of BIPV system

The PV module is composed of solar cell arrays (3×4) whose size is 1266 mm × 1670 mm × 120 mm, and it is accommodated to evaluate the wind-resistance characteristics, which is directly hang on the vertical wall of the demonstration house with dry-suspended method. The wind resistance test based on the ASTM E330 standard is conducted in an approved test chamber at an accredited independent testing laboratory. Applying a test load spectrum allows the structural performance of a BIPV system subjected to an extreme wind event to be assessed. The specified load spectrum should contain a series of varying positive and negative pressure cycles that represent the wind behavior that affects buildings. Using wind pressures between 2400 Pa and 6400 Pa, the study divided the specified load spectrum into five varying positive and negative progressive pressurized phases. For the deflection measurement, three sets of displacement gauges are mounted at various locations along the longitudinal centerline of the windward and leeward surfaces of the BIPV system. Finally, visual inspection based on the visual inspection in section 10.1 of the IEC-61215 standard is conducted to detect any cracking, bending, deformation or damage occurring on the BIPV system in terms of solar cell, connecting junction, and the vibratory looseness of the alumina frames. The experimental results shown in Table 3 indicate that there are no significant deflection and damage after the wind-resistance test.

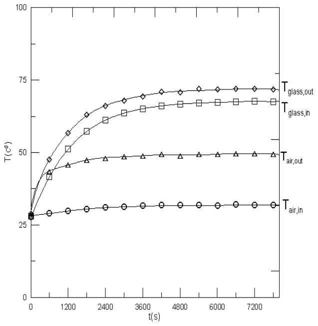

Fig. 2 Histories of the surface temperature ($T_{glass,out}$ and $T_{glass,in}$) and ambient temperature ($T_{air,out}$ and $T_{air,in}$) for proposed PV module.

Table 3 Results of wind resistance test

Interval	Wind pressure (Pa)	Maximum deflection	Maximum Deflection/Span ratio	Visual inspection
01	+2400	0.10 mm	1/15070	No deformation
02	-2400	-0.90 mm	1/1674	No deformation
03	+3400	1.80 mm	1/837	No deformation
04	-3400	-2.00 mm	1/745	No deformation
05	+4400	2.30mm	1/655	No deformation
06	-4400	-2.50 mm	1/603	No deformation
07	+5400	2.90 mm	1/520	No deformation
08	-5400	-3.00 mm	1/502	No deformation
09	6400	3.55 mm	1/425	No deformation
10	-6400	-3.80 mm	1/397	No deformation

3. Full-Scaled Demonstration House Test

The proposed 1kWp BIPV system composed of 6 × 14 PV modules is allocated on a vertical wall of the demonstration house. The length, width, and height of the BIPV system are 604.5, 12, and 259 cm, respectively. Figure 3 shows the scheme of the BIPV system, it is directly hang on the vertical wall of the demonstration house by a dry-suspended method with the novel back anchor system. All structure of the façade contained PV ceramic tile module, an air layer, outer steel frames, Styrofoam insulators, and calcium silicate plates. The temperature on the front side (TF), back side (TB) of BIPV system, the exterior surface (BF), and interior surface (BB) of demonstration house are measured by four K-type thermocouples. The pyranometer coincided with ISO 9060 [7] Second Class is used to sample the irradiation data each time per ten seconds and recorded each time per minute.

Fig. 3 The 1kWp BIPV system was hang on the front surface of a container of transportation

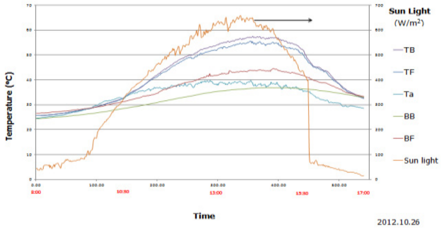

Fig. 4 Temperature measurement on the BIPV system

Figure 4 showed the temperature distribution measured on the front side (TF), back side (TB) of the BIPV system, the exterior surface (BF), interior surface (BB) of the demonstration house and ambient temperature (Ta), respectively. The daily monitoring time is from 8:00 to 17:00. The results indicate that there is no significant temperature variation between the exterior and interior surface of the demonstration house during 8:00~10:00, because the solar radiant intensity was less than 100 W/m^2 before 10:00 a.m. With the increased solar radiant intensity with time, the BIPV system started to generate electrical power and the temperature on the exterior surface of the demonstration house is still lower than that on the front side of the PV system about 10^{0}C. This good insulating effect can ascribe to both high thermal inertia of ceramic tile and a dry-suspended method adopted for the BIPV system. The façade structure can isolate the heat from solar cell irradiation to reduce indoor temperature. Furthermore, there is an air gap between the BIPV system and vertical wall for fluent natural ventilation, which can reduce the thermal accumulation and decreasing the back side temperature of BIPV system. In addition, we used the infrared thermo-image instrument (NEC, TVS-200ES) to detect the temperature distribution of the BIPV system. Figure 5 shows the surface temperature distribution of the BIPV system at 14: 00. The results indicate that the distributed temperature on the perpendicular surface of the BIPV system is almost uniform, and the temperature difference from top to bottom is about 2^0C. Since the proposed BIPV system is perpendicularly hanged on the exterior surface of the demonstration house and the different azimuth of solar irradiance caused the temperature variation. The accumulated electrical energy generated by the proposed BIPV system is 185 kWh during six months monitoring shown in Table 5.

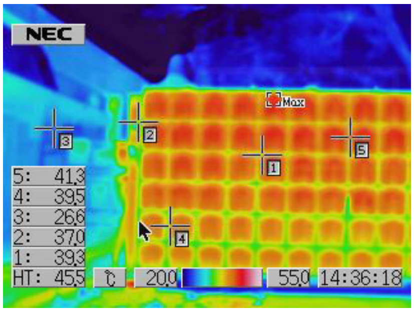

Fig. 5 Temperature distribution on the BIPV system

Table 5 Electrical power accumulation during six months

Experimental period	Accumulated electrical Power Generation (kWh)
Oct. 1–Oct. 31, 2012	53
Nov. 1–Nov. 30, 2012	26
Dec. 1–Dec. 30, 2012	26
Jan. 1–Jan. 31, 2013	28
Feb. 1–Feb. 28, 2013	22
Mar. 1–Mar. 31, 2013	30
Total	185

4. Conclusions

The net zero-energy, zero energy and passive-energy are the trends of the international roadmap process in the energy conservation policy of building section. The BIPV is a design-in concept, which makes the multifunction with the usability of the building materials. Moreover, saving energy, reducing installation cost and modulating the indoor temperature through the design of BIPV system are significant concerns for the building design.

In this work, high thermal inertia of the PV ceramic tile could hinder thermal accumulation and add aesthetic interest as building's façade. Further, the architectural dry-suspended method enhances the efficiency of natural ventilation. After a 50 thermal cycling test, a 200 h humidity-freeze test and a wind-resistance-test, the BIPV system is strong enough to withstand typhoon and humidity climate. Final the 185 kWh accumulated power generation of the proposed BIPV system in a demonstration house during 6 months operation could reduce electrical power generating form fossil fuel. For economic consideration, the average 30 kWh/month electrical power generation is enough applied for an single inhabitan such as air conditioning, a refrigerator, a fan, and indoor lighting. Compared to other renewable energy such as bio-mass, wind energy, and hydrogen energy, the BIPV system integrated with building's façade has the most high energy conversion efficiency, safty, stability and without other allocation sites. The paper gives a sample renewable energy and PV ceramic tile data for renewable energy planners and architectural designers, who are interested in the BIPV applications.

Acknowledgements

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Yen-Chieh Huang was born in Taiwan, in 1984. He received the B.S. degree from the National Sun Yat-Sen University, Taiwan, in 2009. He is a Ph. D. student in the Microelectronics, Department of Electrical and Engineering, National Cheng-Kung University. His research interests include nano-material technology, sensors, dye-senstized solar cell (DSSC) and building integrated photovoltaics (BIPVs).

Shin-Ku Lee was born in Taiwan, in 1971. He received the Ph. D. degree from the National Sun Yat-Sen University, Taiwan, in 2001. He is an assistant research professor in the Research Center for Energy Technology and Strategy, National Cheng-Kung University. His research interests include green building material, building energy management, and building integrated photovoltaics (BIPVs).